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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF THE SECRETARY

BEFORE THE
FEDERAL COMMUNICATIONS COMMISSION
WASHINGTON D. C. 20554

In the Matter of	)	
	)	
	)	
Amendment of Part 90 of the	)	
Commission's Rules to Adopt	)	PR Docket No. 93-61
Regulations for Automatic	)	RM-8013
Vehicle Monitoring Systems	)	

To: The Commission

COMMENTS OF THE TIA MOBILE & PERSONAL COMMUNICATIONS CONSUMER RADIO SECTION

TELECOMMUNICATIONS INDUSTRY ASSOCIATION

Jay E. Padgett
Chairman, TIA MPC
Consumer Radio Section

Daniel L. Bart
Vice President
Telecommunications Industry Association
2001 Pennsylvania Avenue, NW
Suite 800
Washington DC 20006-1813

(202) 457-4936

Dated: March 15, 1994

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SUMMARY

The TIA Mobile & Personal Communications Consumer Radio Section ("the Section") respectfully offers its Comments in response to a Public Notice ("Notice") issued by the Commission requesting Comments on Ex Parte presentations made in association with the above-referenced proceeding. The Notice specifically requested comments on written memoranda summarizing Ex Parte contacts by PacTel Teletrac ("Teletrac") on January 26, 1994, Southwestern Bell Mobile Systems, Inc. ("SBMS") on February 2, 1994 and February 7, 1994, and from MobileVision on February 1, 1994.

It is evident from examination of these memoranda that a Rule Making in this proceeding would be premature at this point, for two reasons. First, as discussed in the "Interim Progress Report" on "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz [Industrial, Scientific, and Medical ("ISM")] Band" included with SBMS' February 2 memorandum, there are a number of key technical questions that remain unanswered. Conclusive answers to these questions, which include the bandwidth requirements of wideband pulse-ranging automatic vehicle monitoring ("AVM") systems, the potential for spectrum-sharing among multiple service providers, and the ability of AVM systems to successfully coexist with the increasing number of unlicensed Part 15 devices in the band, are necessary to support any rational Rule Making process. The authors of the Interim Report indicate their intent to answer these questions with further analysis and simulation studies. Second, due to the lack of answers to these questions, there is no stable or technically supportable proposal upon which to base a Rule Making. In its January 26 memorandum, Teletrac offers a new spectrum-sharing proposal for wideband pulse-ranging AVM systems in the 902-912 MHz band that is radically different from its previous proposal (as conveyed in the Petition filed by Teletrac on May 28, 1992, which initiated this proceeding). Teletrac's new proposal is offered without substantive technical justification. Moreover, as discussed by MobileVision in its memorandum of February 1, Teletrac's new proposal is totally inconsistent with Teletrac's prior positions and the large volume of supporting material which Teletrac has previously filed in this proceeding. The appropriate resolution of this proceeding is now even less clear than it was prior to Teletrac's new proposal.

The Section therefore believes that there is no rational basis upon which the Commission can adopt a set of permanent rules for AVM/LMS systems. A Rule Making must be delayed until the technical questions cited above can be satisfactorily answered, and interested parties can, on the basis of those answers, agree on a technically sound set of operating rules for AVM/location and monitoring services ("LMS") systems. Furthermore, the public interest demands that industry standards be developed to allow interoperability among the systems of different providers to promote inter-system "roaming" and economies of scale in system components. Finally, the Section continues to believe, as supported by its own technical analysis appended to these Comments, that wideband pulse-ranging AVM systems cannot reliably coexist in a band increasingly populated with unlicensed Part 15 devices exhibiting a large variety of transmission characteristics. Accordingly, operation under the existing interim rules should continue until a suitable block of clear spectrum can be identified for wideband pulse-ranging AVM systems (possibly within one of the bands recently identified by the National Telecommunications and Information Administration ("NTIA") for reallocation to the private sector), and an adequate body of technical knowledge can be developed to support industry standards and an appropriate set of rules to govern operation of those systems.

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To: The Commission

COMMENTS

I. INTRODUCTION

1. The Telecommunications Industry Association ("TIA") Mobile & Personal Communications Consumer Radio Section ("the Section") hereby offers its Comments in response to a Public Notice ("Notice") issued by the Commission[1] requesting Comments on Ex Parte presentations associated with the above-referenced proceeding. The Notice specifically requested comments on written memoranda summarizing Ex Parte contacts by PacTel Teletrac ("Teletrac") on January 26, 1994, Southwestern Bell Mobile Systems, Inc. ("SBMS") on February 2, 1994 and February 7, 1994, and from MobileVision on February 1, 1994.

1. FCC Public Notice DA 94-129, February 9, 1994.

2. The Notice states that these Ex Parte presentations "raise new issues that warrant giving interested parties an additional opportunity for comment. Specifically, these presentations address alternatives for the licensing of wideband multilateration AVM systems." The Notice cites as an example the different possible definitions of licensing boundaries.

3. The Section agrees that the issue of licensing boundaries is important in the consideration of any action by the Commission that will provide valuable spectrum for a licensed service. However, there are other issues raised by the memoranda of Teletrac, SBMS, and MobileVision that are equally important and perhaps less easily resolved than that of licensing boundaries. These include (1) the bandwidth requirements and frequency channelization plan for AVM/LMS, (2) the number of service providers allowed per area and the sharing of spectrum among providers, and (3) the ability of wideband pulse-ranging AVM/LMS systems to function in the presence of the random interference that will increasingly characterize the 902-928 MHz band.

4. As discussed below, the Ex Parte memoranda referenced by the Notice clearly show that a Rule Making in this proceeding would be premature due to the lack of answers to key technical questions, and the resulting absence of a stable proposal for Rules governing wideband pulse-ranging AVM systems.

II. THE WORK DISCUSSED IN THE SBMS/VIRGINIA TECH INTERIM REPORT SHOULD BE COMPLETED PRIOR TO A RULE MAKING

5. SBMS, in its February 2, 1994 Ex Parte letter, included an "Interim Progress Report" from the Mobile and Portable Radio Research Group at Virginia Tech ("the Virginia Tech report")[2] which discusses some of the technical issues that have been at the forefront during this proceeding. These include (1) means of sharing spectrum among multiple AVM/LMS providers, (2) bandwidth vs. capacity, and (3)

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2. "Capacity and Interference Resistance of Spread-Spectrum Automatic Vehicle Monitoring Systems in the 902-928 MHz ISM Band," Rick Cameron and Brian D. Woerner, Mobile and Portable Radio Research Group, Bradley Department of Electrical Engineering, Virginia Tech, January 14, 1994.

interference with Part 15 devices. While the report correctly identifies these and several others as key issues that must be resolved before a reasoned decision can be made in this proceeding, it primarily offers only general qualitative assessments and proposes specific quantitative analyses of the issues as future work. The Section believes that completion of this work would greatly improve the quality of the Commission's decision-making process. As noted in the Virginia Tech report, "We believe that this study will be useful to the FCC in formulating rules for the operation of AVM systems." [3] The Section would go even further and assert that the information which the Virginia Tech report proposes to develop is a prerequisite to a well-founded Rule Making.

6. Two of the issues that are discussed in the Virginia Tech report but are not quantitatively resolved have already been addressed quantitatively by the Section in its Ex Parte presentation to FCC Private Radio Bureau ("PRB") Bureau Chief Ralph Haller and members of his staff on October 22, 1993. The attached report (Exhibit A), "Analysis of Teletrac Receiver Performance and Part 15 Interference" ("the Section's report") was provided to the PRB at that meeting and included in the record of this proceeding. The Section's report addresses quantitatively two topics that are also discussed in the Virginia Tech report: (1) interference from Part 15 devices to the receivers of wideband pulse-ranging systems, and (2) the bandwidth vs. capacity tradeoff. Although the authors of the Virginia Tech report were evidently unaware of the Section's report, the assessment in the Virginia Tech report is largely in agreement with the Section's conclusions on these two topics.

7. In §3 of the Section's report, it is shown that the "bandwidth squared" capacity increase claimed by Teletrac on the basis of the Cramer-Rao bound[4] is illusory if the receiver threshold is taken into account.[5] Although the Virginia Tech report

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3. Virginia Tech report at p. 5.
4. See Appendix 1 of Teletrac's Comments, entitled "Engineering Analysis of Cochannel Pulse-Ranging LMS Systems," Professor Raymond Pickholtz, June 28, 1993.
5. Indeed, as shown in the Section's report, once the message duration has been shortened to the point at which the carrier-to-noise ratio at the edge of coverage for a given base site is equal to the receiver threshold, further reductions in message duration (to increase capacity) require that the bandwidth increase as the inverse squared of the message duration, so capacity increases as the square root of the bandwidth (see pp. 7-8 of the Section's report). At that point, subdividing systems provides additional capacity more efficiently than

does not consider this effect, it states in its discussion of "Future Work" that:

> If we view each position location transmission as the transmission of a message, it seems unlikely that the number of messages could increase indefinitely with the square of bandwidth. We believe that the Cramer-Rao bound may hold only for certain detection methods or within a certain range of system operation. We hope to reconcile these conflicting results with further study.[6]

As discussed above, the Section's analysis confirms the intuition of the Virginia Tech report's authors.

8. To the Section's knowledge, the relationship between capacity and bandwidth in the presence of multipath has not yet been explored. This would seem to be a significant deficiency in the existing record, that, in the Section's view, should be corrected prior to any Rule Making by the Commission. The Virginia Tech report offers some heuristic reasoning based on experience with wideband communication systems (as distinguished from location systems) which suggests that "In the range of 1 MHz to 10 MHz, wider bandwidth will result in some modest improvements in multipath rejection."[7] This assessment derives from the ability of a wideband receiver to resolve multipath components using RAKE receiver techniques, thereby obtaining a form of diversity (independently-faded channels that can be combined in some manner) and reducing the overall power variation of the received signal power due to multipath. For a communication link (e.g., in a spread-spectrum cellular system), the net effect is to reduce the amount of carrier-to-noise "margin" that must be allowed in the link budget for multipath fading, thereby increasing the coverage area for a given transmitted power, antenna gain, receiver sensitivity, etc. It is unclear at this point that the multipath-resolution capabilities of a wideband signal apply to ranging systems in the same way that they apply to communications systems. The Section therefore believes that further study is warranted. The Virginia Tech report recognizes this; one of the

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increasing the bandwidth of a single system.

6. Virginia Tech report at p. 11.
7. Virginia Tech report at p. 9.

topics identified in its "Future Work" discussion is "simulation of position location in multipath interference and impulsive noise." [8]

9. The Virginia Tech report also discusses interference between Part 15 devices and AVM systems. While stating that "the interference issues involving AVM systems and Part 15 devices will require significant further study to resolve," [9] the Virginia Tech report offers "qualitative conclusions" [10] including:

> [W]hen a Part 15 device is operating much closer to a base station than an AVM mobile unit, the transmitted power is large enough to produce a significant near/far problem. In the other direction, Part 15 devices operating indoors and over short distances are unlikely to experience significant interference from AVM systems. However, Part 15 devices designed for outdoor operation m[a]y experience significant interference. Some interference rejection techniques may be available to address narrowband interference from Part 15 devices.[11]

10. The Section partially agrees with this assessment. As shown using propagation and signal strength calculations in §4 of the Section's report, the "near/far" problem can be quite severe, and interference with the reverse link (mobile-to-base) of the AVM system from Part 15 devices near the AVM base station can be devastating. However, the Section does not believe that most Part 15 devices, either indoor or outdoor, will sustain any appreciable interference from AVM systems. The signal transmitted by the mobile is on the order of 1 watt effective radiated power ("ERP"), extremely short in duration (on the order of 10 milliseconds), and wideband (3 to 4 MHz in current systems). Since the mobile transmitter is typically within 6 feet of the ground, the propagation path between it and the Part 15 devices normally will be very poor and will highly attenuate the signal. In combination, these factors nearly eliminate the possibility that AVM

8. Virginia Tech report at p. 11.
9. Virginia Tech report at p. 9.
10. Id.
11. Id.

mobile transmissions will cause any significant interference problems for Part 15 devices. Although the AVM forward link signal is high power (on the order of 300 watts) and emanates from an elevated base station with a good antenna, it is relatively narrow in bandwidth (250 kHz or less) and can easily be avoided by adaptive, frequency-agile Part 15 devices designed to operate in a hostile interference environment.

11. It is unlikely that "interference rejection techniques" will be effective in mitigating the effects of Part 15 interference on the AVM reverse link. To operate under §15.247 of the Commission's Rules, Part 15 devices are required to use either frequency hopping or direct sequence modulation. When viewed at a given instant in time, a frequency hopping signal is indeed narrowband, but it is required to randomly hop between at least 50 different frequency channels. Direct sequence systems are required under §15.247 to use a processing gain of at least 10 dB, and to have a bandwidth of at least 500 kHz. Beyond these general requirements (and several others relating to parameters such as out-of-band signal power), §15.247 allows considerable design freedom. The result is a growing number of different Part 15 designs using a wide variety of bandwidths, modulation formats, hopping rates, interference avoidance strategies, etc. The Section believes that this diversity in Part 15 operating characteristics will render the task of adaptive interference rejection for a fixed-frequency AVM receiver virtually impossible. The Section's report (§4.3) provides a brief general discussion of the implications of the requirements of §15.247 on AVM receiver performance.

12. In its summary, the Virginia Tech report concludes that "Interference between AVM and Part 15 devices should remain within tolerable limits provided that these systems do not operate in close proximity; however, interference is certainly possible for closely located systems." [12] The conclusions of the Virginia Tech report are distilled and represented in the body of the SBMS February 2, 1994 memorandum by the statement "LMS and Part 15 systems should be able to coexist in spectrum." [13] Due to the factors mentioned supra and discussed in

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12. Virginia Tech report at p. 10.

13. SBMS February 2, 1994 memorandum on p. 5 (captioned "Virginia Tech Interim Report Summary."

more detail in the Section's report, the Section believes that this statement is an oversimplification, and is somewhat misleading. Further, it implies a level of certainty about the conclusion that directly contradicts the above-referenced statement in the Virginia Tech report that "the interference issues involving AVM systems and Part 15 devices will require significant further study to resolve." [14]

13. Finally, it should be noted that in response to a suggestion made by PRB Chief Haller during the Section's October 22, 1993 meeting with him, the Section has repeatedly attempted to organize a test program in cooperation with other Part 15 manufacturers and Teletrac to verify the Section's analysis of the potential for interference from Part 15 devices to wideband pulse-ranging AVM systems. To date, Teletrac has been unwilling to cooperate in such a program. Correspondence between the Section and Teletrac in this matter has been associated with the record of this proceeding.

III. A STABLE PROPOSAL FOR AVM/LMS RULES UPON WHICH TO BASE A RULE MAKING DOES NOT YET EXIST

14. In its January 26, 1994 Ex Parte letter, Teletrac offers a new proposal for wideband AVM/LMS systems whereby two such systems would be allowed to operate in any given licensing area, sharing the 902-912 MHz band on a cochannel basis. As discussed at length by MobileVision in its February 1, 1994 Ex Parte letter[15] this proposal represents a radical departure from Teletrac's previous positions during this proceeding, and seems inconsistent with Teletrac's prior claims that band-sharing between two wideband pulse-ranging systems in the same area is not feasible.[16] As also noted by MobileVision,[17] Teletrac offers this new proposal without substantive technical support or any evidence of detailed analysis. The main factor that Teletrac's new proposal seems to have in common with the original proposal in its Petition is that it would allow Teletrac to continue operating its current system without significant modifications.

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14. Virginia Tech report, op. cit.
15. See MobileVision at pp. 3-5.
16. See for example, Pickholtz, op. cit.
17. MobileVision at p. 5.

15. Teletrac states that its new proposal "improves the environment for Part 15 devices." [18] The basis for this claim is unclear. As explained supra, interference to Part 15 devices from AVM systems is not a serious technical issue in this proceeding. Rather, the concern is interference from Part 15 devices to the reverse link of wideband pulse-ranging AVM systems. The Section does not believe that Teletrac's new proposal would reduce the potential for such interference to any degree whatsoever. In fact, it might be argued that Part 15 interference will be more acutely felt by two AVM providers attempting to share a single band as Teletrac proposes.

16. Teletrac's new proposal also raises another issue which heretofore seems to have been given little attention in this proceeding, but is important when the public interest is considered. To illustrate the need for sharing rules, Teletrac gives the example that "a system might be built in New Jersey requiring a certain protocol, but a system built in New York would require an entirely different protocol. Under this scenario, a vehicle traveling from Washington D.C. could not receive service when traveling to New York." [19]

17. Adoption of sharing rules will not necessarily solve this problem. While it may be possible to develop a set of sharing rules that will allow more than one provider to coexist in the same band, that set of rules will not necessarily guarantee interoperability among the systems of different service providers. Sharing rules will simply regulate access to the physical channel, and might be viewed as a "layer 0" protocol. For interoperability (analogous to "roaming" in cellular systems), harmonization of the higher layers is necessary. As a practical matter, this can be achieved only with an industry standard, such as those that exist for cellular systems. If the public policy objective to be served by this proceeding is the widespread availability of Intelligent Vehicle Highway Systems ("IVHS") to the public, such standards would seem to be essential, to encourage system compatibility and promote the scale economies necessary to minimize system component costs. In fact, in response to a request from IVHS America, TIA's

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18. Teletrac at p. 1.
19. Id.

Mobile & Personal Communications ("MPC") Division has recently created an IVHS Section to recommend IVHS standards as appropriate to benefit the public interest.[20]

18. In sum, the Ex Parte memoranda referenced by the Notice show that the current status of this proceeding, and that of wideband pulse-ranging systems in general, fall far short of the maturity necessary for a well-considered Rule Making that supports the public interest.

IV. IF WIDEBAND PULSE-RANGING SYSTEMS ARE IN THE PUBLIC INTEREST, THE COMMISSION SHOULD GRANT THEM AN EXCLUSIVE ALLOCATION IN THE SPECTRUM TO BE RELEASED BY NTIA

19. As evidenced by the variety of AVM systems described in the record of this proceeding, the existing interim rules have provided a valuable test bed in the 902-928 MHz band for the development of these systems. The Section continues to believe that "local area" AVM systems[21] (regardless of whether they are "wideband" or "narrowband") may be able to continue successful operation in the 902-928 MHz band without suffering significant performance degradation from the interference in that band. However, the Section also believes that over time, the performance of wideband pulse-ranging systems will be increasingly degraded by that interference. If the Commission judges that the availability of wideband pulse-ranging systems is in the public interest, that interest would be ill-served by a situation in which the reliability of those systems progressively deteriorates while the demand for their services increases. The Section therefore believes that if the deployment of wideband pulse ranging systems is found to serve the public interest, then those systems must be provided with a clear band of spectrum in which to operate reliably.

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20. The new IVHS Section was established during the TIA MPC Division meeting on November 17, 1993. A TIA press release describing the new Section is attached as Exhibit B.

21. An example of a "local area" system is an automatic toll-registration system.

20. The National Telecommunications and Information Administration ("NTIA") has recently released a preliminary report identifying 200 MHz of spectrum for reallocation from the federal government to the private sector.[22] The Section believes that if it is in the public interest, the Commission should consider allocating some of this spectrum to wideband pulse-ranging systems. The bands 2390-2400 MHz, 2402-2417 MHz, and 4660-4685 MHz are targeted for "immediate" and exclusive (non-federal) reallocation to the private sector. The remaining 150 MHz is targeted for reallocation over the next 15 years, some on an exclusive basis and some on a shared federal/non-federal basis. This includes the band 2300-2310 MHz, which is targeted for exclusive reallocation to non-federal use by January, 1996. If, as Teletrac now claims, 10 MHz is sufficient for wideband pulse-ranging systems, the bands 2300-2310 MHz and 2390-2400 MHz would appear to be ideal candidates.

21. The Section therefore urges the Commission to consider allocating some of the spectrum to be reallocated from NTIA to wideband pulse-ranging systems, if such systems are judged to serve the public interest.

V. CONCLUSION

22. The Section concludes that, based on the Ex Parte memoranda of Teletrac, SBMS, and MobileVision, in addition to the issues about licensing area boundaries that have been raised, there remain some unresolved fundamental technical questions in this proceeding. Moreover, the recent changes in Teletrac's proposal, and the negative reactions of other potential AVM service providers, evidence a disturbing lack of stability in the details of the proposed Rules for AVM/LMS. The Section therefore concludes that a Rule Making in this proceeding would be premature. Absent conclusive showings to the contrary, the Section continues to believe that the nature of the 902-928 MHz band, characterized by an increasing number of uncontrolled interference sources, represents an environment that is incompatible with the objective of providing reliable, high-

22. NTIA Special Publication 94-27, "Preliminary Spectrum Reallocation Report," February, 1994.

quality location and monitoring services. If the general availability of such services is in the public interest, then it is incumbent upon the Commission to identify an appropriate band that is clear of uncontrolled interference. The spectrum recently identified by NTIA for reallocation from the federal government to the private sector includes several bands that appear well-suited for meeting this need. The Section believes that the Commission should terminate this proceeding and allow continued operation of AVM systems under the present interim rules while initiating the process of identifying suitable clear spectrum. In parallel with that activity, the AVM industry should work to resolve the unanswered technical questions discussed herein, and to develop a set of industry standards for AVM/LMS systems that support the public interest.

Respectfully submitted,

TELECOMMUNICATIONS INDUSTRY ASSOCIATION

MOBILE & PERSONAL COMMUNICATIONS CONSUMER RADIO SECTION

Jay E. Padgett, Chairman
Mobile & Personal Communications
Consumer Radio Section

Daniel L. Bart, Vice President
Telecommunications Industry Association
2001 Pennsylvania Avenue, NW
Suite 800
Washington, DC 20006-1813
(202) 457-4936

March 15, 1994

EXHIBIT A

ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

Dr. Jay E. Padgett
Chairman, TIA Mobile & Personal Communications
Consumer Radio Section

October 22, 1993

EXECUTIVE SUMMARY

The FCC has adopted an NPRM in PR Docket 93-61, proposing to establish permanent provisions under Part 90 of its Rules for Automatic Vehicle Monitoring (AVM) systems in the 902-928 MHz ISM band. This proposal was made in response to a Petition filed in 1992 by PacTel Teletrac, which operates a wideband pulse-ranging AVM system in several metropolitan areas under the existing interim Part 90 Rules. The function of this system is to locate vehicles using a multilateration technique, whereby the vehicle responds to a narrowband high-power paging signal (the forward link) by transmitting a short (10-20 milliseconds) low-power wideband burst (the reverse link). This burst is received by multiple Teletrac base station receivers, each of which estimates the relative time of arrival (TOA) of the signal. Using the TOA estimates from the receivers and knowledge of their positions, the system can compute the location of the vehicle within several hundred feet.

One potential problem with this system is its vulnerability to interference from the unlicensed Part 15 devices that will be increasingly prevalent in this band. The purpose of this paper is to present an analysis of that interference and its effect on the Teletrac base station receivers. Teletrac contends that this interference will not present a problem to its system, but the analysis presented here shows otherwise. While the received signal power from a vehicle several miles from the base station will be on the order of -100 dBm (more or less depending on the base antenna elevation and the distance to the vehicle), the interference power from a Part 15 device several thousand feet from the base can be in the range of -40 to -60 dBm. The Teletrac receiver uses direct sequence modulation (a spread spectrum technique), which provides a processing gain that allows the receiver to operate satisfactorily with carrier-to-interference ratios as low as -25 dB (i.e., the desired signal 25 dB *below* the interference at the receiver). However, in the presence of interference that exceeds the desired signal by 40 dB or more, the receiver is operating far below its threshold and the TOA estimation error is so large that the receiver is essentially useless in contributing to the location estimate.* Widespread deployment of Part 15 devices, which are randomly located and uncontrolled,

* The simulation results reported by Teletrac in its Petition suggest that with a -40 dB carrier-to-interference ratio, the TOA estimation error can exceed 1 mile.

clearly could have a devastating effect on the performance and reliability of the Teletrac system.

The analysis provided here shows further that the relationship between bandwidth and capacity claimed by Teletrac and used to support the need for an 8 MHz reverse-link bandwidth is flawed. Teletrac claims in its Comments and Reply Comments that, based on the Cramer-Rao bound, which gives the theoretical lower limit on TOA estimation error, the required message length is inversely proportional to the square of the bandwidth, so that if the bandwidth is doubled, the message length can be reduced by a factor of four, quadrupling capacity. This claim, however, fails to account for the effect of the receiver threshold, and therefore is unrealistic.

As shown in this paper, the simulation results reported by Teletrac in its Petition, taken together with the receiver characteristic disclosed in Teletrac's Comments, suggest that once the receiver has reached its threshold, the minimum message duration varies as the inverse square root, rather than the inverse square, of the bandwidth. Consequently, to double the capacity, the bandwidth must be increased by a factor of four. Increasing the bandwidth from 4 MHz to 8 MHz will increase capacity by only about 40% (whereas capacity could be doubled by operating two systems on separate 4 MHz bands). Moreover, the Part 15 interference problem identified here cannot be solved even by increasing the bandwidth and holding the message length constant (thereby increasing the processing gain).

It is concluded that Part 15 devices represent a potentially serious threat to the viability of wideband pulse-ranging systems operating in the 902-928 MHz band, and regardless of the severity of the threat from Part 15 devices, increasing the bandwidth to gain capacity is not a worthwhile tradeoff. These conclusions imply that (1) the 902-928 MHz band, with its high potential for uncontrolled interference, may not be the appropriate band for wideband pulse-ranging systems such as Teletrac's, and (2) that 8 MHz per system may not be necessary in any event. These two points in turn suggest that another band should be sought for those systems, and the spectrum requirement may not be as great as has been assumed.

ANALYSIS OF TELETRAC RECEIVER PERFORMANCE AND PART 15 INTERFERENCE

1. INTRODUCTION

This paper presents an analysis of the potential for interference from Part 15 devices that operate in the 902-928 ISM (Industrial, Scientific, and Medical) band into the the receivers used by Pactel Teletrac's wideband pulse-ranging system. Those receivers are designed to estimate the relative time-of-arrival (TOA) of a signal pulse from the vehicle to be located. The TOA estimates from multiple receivers at different locations then are used by the central system processor to estimate the location of the vehicle via multilateration.

The focus of this paper is the performance of an individual receiver operating in the presence of cochannel interference. The objective is to develop an understanding of the degree to which Part 15 devices can corrupt the TOA estimate of an individual receiver. Section 2 reviews the fundamental theoretical limit on the TOA estimation error (the Cramer-Rao bound) as well as the measured performance of the Teletrac receiver. Section 3 analyzes the receiver threshold effect and its implications on the ability to improve system throughput by increasing the bandwidth. Section 4 discusses propagation and the signal power received by the base stations from both the desired transmitter and from interfering Part 15 transmitters. Section 5 discusses the conclusions.

Reference is made to Teletrac's Petition [1] as well as the Comments [2] and Reply Comments [3] that Teletrac filed with the FCC in response to the NPRM on PR Docket 93-61 [4], and to the technical Appendices of [1] and [2].

2. TOA ESTIMATION ERROR FOR RECEIVER OPERATING ABOVE THRESHOLD

2.1 The Cramer-Rao Bound

The receiver must provide an estimate of the TOA of a received signal burst. The measure of how effectively it does this is the rms TOA estimation error, denoted here by σ_t. As discussed in Appendices 1 and 2 of Teletrac's Comments, and also in the literature [5][6], the minimum mean-squared TOA estimation error is given by the Cramer-Rao bound as

$$\sigma_t^2 \geq \left[\beta^2 2E/N_0\right]^{-1}, \tag{1}$$

where E is the total received energy in the message, $N_0/2$ is the two-sided noise spectral power density, and β is the "effective bandwidth" or "Gabor bandwidth", given by

$$\beta^2 = \frac{\int_{-\infty}^{\infty} \omega^2 \,|\, S(\omega) \,|^2 d\omega}{\int_{-\infty}^{\infty} |\, S(\omega) \,|^2 d\omega} . \tag{2}$$

$S(\omega)$ is the equivalent baseband signal spectrum (i.e., the Fourier transform of the signal). If the occupied bandwidth is limited to W Hz, then the integrals in (2) would be taken between $-W/2$ and $W/2$.

If C is the received RF carrier (desired signal) power and T is the message length, then $E = CT$. As noted by Teletrac in Appendix 2 of its Comments[1] spread spectrum (direct sequence modulation) is used. This is to give a short pulse rise time without reducing the energy per message ("E" in eq. 1).

Assuming that cochannel interference has the same effect on receiver performance as additive Gaussian noise of the same total power,[2] and B is the receiver noise bandwidth, then by definition $N_0 = N/B$, where N is understood to be the total thermal noise plus cochannel interference power as seen by the receiver. Letting T_C denote the chip duration, and defining $k_{BT} \triangleq BT_C$ (a constant which depends on the modulation and the degree of sidelobe truncation in the frequency domain[3]), (1) can be written as

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}\beta^2 T(C/N)} , \tag{3}$$

where C/N is the RF carrier-to-noise ratio.

Letting $k_\beta \triangleq \beta/B$, (3) becomes

1. "Theoretical and Field Performance of Radiolocation Systems," PacTel Teletrac, June 25, 1993, Appendix 2 of Teletrac's Comments [2].
2. With a spread spectrum system, this is a reasonable assumption for purposes of analysis, because the receiver correlates the received signal with the high-rate "pseudonoise" (PN) code waveform, which collapses the desired signal to its information bandwidth but spreads the interference over the entire spread bandwidth, and randomizes it.
3. This depends on the filtering of the received signal.

$$\sigma_t^2 \geq \frac{T_C}{2k_{BT}k_\beta^2 B^2 T(C/N)}. \tag{4}$$

Clearly, $k_{BT}k_\beta = \beta T_C$, which is the same as the parameter "a" given in Appendix 2A of Teletrac's Comments.[4]. With $R = 1/T_C$ (the chip rate), (4) can also be expressed in the form of eq. A24 of Teletrac's Appendix 2A as

$$\sigma_t^2 \geq \frac{T_C}{2(k_{BT}k_\beta)^2 RBT(C/N)}. \tag{5}$$

2.2 Teletrac's Receiver Performance

Teletrac's Petition and Comments suggest the following system parameters: $R = 1.7$ Mchip/s, $T \approx 14$ milliseconds (70 messages/second), and $k_{BT}k_\beta = 1.875$ (corresponding to "Phase-shaped" BPSK modulation, from Table 1 of Teletrac's Appendix 2A).[5] Assuming $B = 2R$ (which appears consistent with eq. A25 of Teletrac's Appendix 2A), the Cramer-Rao bound on σ_t for the Teletrac receiver would be roughly $\sigma_t \geq 1/\sqrt{C/N}$ (nanoseconds). This is close to (but slightly below) the "Cramer-Rao bound" curve shown in Figure 12 of Teletrac's Appendix 2, reproduced here as Fig. 1. The curve representing Teletrac's measured receiver performance is roughly described by

$$\sigma_t \approx \frac{2}{\sqrt{C/N}} \text{ (nanosec)}. \tag{6}$$

Thus, the receiver's actual performance is about 6 dB worse than the Cramer-Rao bound calculated from the parameters estimated above, and about 5 dB worse than the "Cramer-Rao bound" curve in Fig. 1. It should be noted, however, that even the Cramer-Rao bound is design-dependent, because of the parameter k_β, which depends on the spectral shape of the

4. "Impact of Wide-band Co-channel Interference on the Accuracy of Hyperbolic Location," prepared by Emmanuel Wildauer, PacTel Teletrac, June 22, 1993, Appendix A to Appendix 2 of Teletrac's Comments [2].

5. The integration limits used to compute the values of $k_{BT}k_\beta$ for various modulation formats in Table 1 of Teletrac's Appendix 2A were not stated.

transmitted waveform.

3. THE EFFECT OF THE RECEIVER THRESHOLD

3.1 Mathematical Model

As noted in Appendix 1 of Teletrac's Comments,[6] the performance of the receiver follows the form of the Cramer-Rao bound only as long as the carrier-to-noise ratio is above some threshold. This receiver threshold effect limits the ability to increase capacity (reduce message duration) by increasing the bandwidth. To understand this limitation, (1) can be written as

$$\sigma_t^2 = \frac{k_R}{2\beta^2 n \cdot [f(E_b/N_0)]} , \tag{7}$$

where k_R represents the effect of receiver non-ideality during normal operation (i.e., a fixed dB offset from the Cramer-Rao bound). The parameter n represents the number of information bits in the message,[7] and E_b is the energy per bit, so $E = nE_b$. The function $f(\cdot)$ is defined as:

$$\begin{aligned} f(x) &= x , \quad x \geq x_0 \\ &= f_2(x) , \quad 0 < x < x_0 \end{aligned} \tag{8}$$

where $f_2(\cdot)$ is some unknown function and x_0 is the E_b/N_0 threshold, below which receiver performance no longer adheres to the form of the Cramer-Rao bound. For continuity, $f_2(x_0) = x_0$.

It is useful to normalize by defining a second function $g(\cdot)$ as

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6. "Engineering Analysis of Cochannel Pulse-Ranging LMS Systems," Professor Raymond Pickholtz, June 28, 1993, Appendix 1 of Teletrac's Comments [2].
7. For a pure locating application (no information transmitted), $n = 1$. Eq. (7) presumes that for $n > 1$, a TOA estimate is generated for each received bit, then the n estimates are averaged to yield an aggregate estimate. The variance of n independent estimates will be less than that of each individual estimate by a factor of n.

$$g(\xi) \triangleq \frac{f(x_0\xi)}{x_0}, \tag{9}$$

hence, $f(x) = x_0 g(x/x_0)$. It is clear from (8) that for $\xi \geq 1$, $g(\xi) = \xi$ and for $\xi < 1$, $g(\xi) = g_2(\xi) \triangleq f_2(x_0\xi)/x_0$.[8]

If T_b is the duration of a bit, then $E_b = CT_b$ (the total message duration is $T = nT_b$). Since the objective here is to explore the limitations on trading-off the bandwidth B against the message duration T, it will be assumed that C, N_0, and n are fixed. If T_0 represents the bit duration for which the receiver operates exactly at threshold, then by definition

$$T_0 = \frac{N_0 x_0}{C}. \tag{10}$$

Letting $\beta = k_\beta B$ as before, and aggregating fixed factors into a single constant, (7) becomes

$$\sigma_t^2 = \frac{k}{B^2 n[g(T_b/T_0)]} \tag{11}$$

where

$$k \triangleq \frac{k_R}{2k_\beta^2 x_0}. \tag{12}$$

Letting σ_0 represent the maximum acceptable value of σ_t, (11) gives

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8. This is valid for any $f_2(x)$ for which a power series expansion exists; if $f_2(x) = \sum_{i=0}^{\infty} a_i x^i$ then $g_2(\xi) = \sum_{i=0}^{\infty} b_i \xi^i$, with $b_i = a_i x_0^{i-1}$.

$$g(T_b/T_0) = \frac{k}{B^2 n \sigma_0^2} \,. \tag{13}$$

If B_0 is the bandwidth for which $\sigma_t = \sigma_0$ when the receiver is operating at threshold (i.e., $T_b = T_0$), then from (13), with $g(T_b/T_0) = 1$,

$$B_0^2 = \frac{k}{n\sigma_0^2} \,. \tag{14}$$

Hence, (13) can be written as

$$g(T_b/T_0) = \left(\frac{B}{B_0}\right)^{-2} . \tag{15}$$

For $T_b \geq T_0$, $g(T_b/T_0) = T_b/T_0$ and (15) gives the relationship that T $(= nT_b)$ decreases inversely with B^2, used by Teletrac to argue that maximum capacity (messages per second) increases as the square of the bandwidth (see, for example, p. 21 of Appendix 1 to Teletrac's Comments). However, for $T_b < T_0$, $g(T_b/T_0)$ behaves differently. To understand the effect of increasing bandwidth when $T_b < T_0$, the behavior of $g(\xi)$ for $\xi < 1$ must be understood.

This behavior can be inferred from the first analysis provided by Teletrac in Appendix 2 of its Petition for Rule Making,[9] and the receiver performance curve provided by Teletrac in Appendix 2 of its Comments (Fig. 1 of this paper). In the first analysis of Appendix 2 of its Petition, Teletrac illustrated the effects of cochannel interference with an idealized example. As shown in Fig. 2, the vehicle to be located was positioned at the center of a square 10 miles on a side, and a receiver base station was on each corner of the square. An interference source was 7000 feet to the left of the upper left base station (designated "site A" for purposes of this discussion). Teletrac computed the location error at the 95th percentile as a function of the RF power radiated by the interference source. A 5 watt transmit power with an antenna gain of -6 dBi was assumed for the vehicle, giving an ERP of 1.25 watts. Path loss

9. "Impact of Co-channel Interference on 900 MHz Wideband Pulse-ranging AVM System Performance," PacTel Teletrac, April 6, 1992, Appendix 2 of Teletrac's Petition [1].

was taken to vary as d^4 (i.e., 12 dB per octave or 40 dB per decade), and fading effects (multipath, shadowing) were ignored. Specific system parameters such as base tower height, chip rate, receiver noise bandwidth/noise figure, and message duration were not disclosed. However, it was stated that the cochannel interference source was assumed to be at ground level (presumably representing a mobile unit).

Based on the information available, the C/I at each base station can be computed as a function of the RF power transmitted by the interference source, as shown in Figure 3.[10] Since the C/I at the other 3 sites is much higher than site A, those receivers should contribute negligible error (several feet or less) to the location estimate, assuming that Teletrac's analysis used the receiver characteristic reported in Appendix 2 of its Comments.

It thus appears that site A is dominating the overall location estimation error. If this is the case, the location error vs. the C/I at site A should accurately reflect the ranging error vs. C/I performance of a single receiver. Fig. 4 shows the location error from the study in Teletrac's Petition vs. the C/I at site A.[11] Also shown on Fig. 4 is the plot of $\sigma_r = 2/\sqrt{C/I}$ feet (dashed), which represents the rms ranging error (in feet) for Teletrac's receiver operating above threshold (i.e., $T > T_0$). The offset between the σ_r curve and the location error curve presumably occurs because the error curve represents the ninety-fifth percentile, while the σ_r curve represents the standard deviation of the estimation error. For most distributions, the ninety-fifth percentile will be more than one standard deviation above the mean (assuming an unbiased estimator, the mean is zero in this case).

The regression curve shown is actually the concatenation of a second-order regression (dashed) through the lower four points and a linear regression (solid) for all points except the lower three. This curve suggests that the receiver behaves in accordance with Fig. 1 provided C/I is above a threshold of roughly -25 dB. As C/I drops below -25 dB, the error begins to increase more rapidly than the inverse square-root of C/I. Once C/I drops below about -30 dB, the error vs. C/I characteristic becomes roughly inverse-square; that is, $\sigma_r \propto (C/I)^{-2}$. Thus, σ_t varies as $1/\sqrt{C/I}$ for $C/I \geq -25\,\text{dB}$, and as $1/(C/I)^2$ for $C/I < 30\,\text{dB}$. The range $-25\,\text{dB} > C/I > -30\,\text{dB}$ is a transition region between the inverse square-root and inverse square variations. During discussions with Teletrac representatives [9], it was confirmed that a C/I of -25 dB is roughly the practical lower carrier-to-noise limit of operation for the receiver.

This suggests that $f_2(x)$ can be modeled as $f_2(x) = x_0(x/x_0)^4$, so $g_2(\xi) = \xi^4$. Using this model for $g_2(\xi)$, (15) gives the tradeoff between T_b and B as

10. Fig. 3 is the same as Fig. 1 of the TIA Consumer Radio Section's Comments [7].

11. Fig. 4 is a modified version of Fig. 2 of the TIA Consumer Radio Section's Reply Comments [8].

$$T_b/T_0 = (B/B_0)^{-2}\,, \quad T_b \geq T_0 \tag{16a}$$

$$T_b/T_0 = (B/B_0)^{-1/2}\,, \quad T_b < T_0\,. \tag{16b}$$

Hence, the bandwidth-squared capacity increase applies only for $B \leq B_0$, and capacity cannot be increased as B^2 indefinitely. For $B > B_0$, the rate of increase slows to a square-root law, at which point it clearly is more efficient to increase capacity by using two separate frequency bands. Fig. 5 shows a piecewise-log-linear plot of T_b/T_0 vs. B/B_0.

3.2 Receiver Threshold - Summary and Implications

The results just derived may be summarized as follows:

1. The value of T_b for which the receiver operates exactly at threshold is T_0, given by (10) as $T_0 = N_0 x_0/C$. Reducing T_b below T_0 (assuming N_0, x_0, and C are fixed) will cause E_b/N_0 to drop below the threshold x_0, whether or not the bandwidth is increased.

2. The required bandwidth for an rms TOA estimation error of σ_0 when the receiver is operating at threshold (i.e., $E_b/N_0 = x_0$) is given by (14) as $B_0^2 = k/n\sigma_0^2$, where $k = k_R/2k_\beta^2 x_0$, $k_\beta = \beta/B$ (which depends on the shape of the desired signal spectrum), and n is the number of information bits in the message. For a pure locating application, $n = 1$. For Teletrac's receiver, $\sigma_0 \approx 35$ nanosec for $C/I = -25$ dB, which appears to be the threshold for Teletrac's current-generation receiver parameters.

3. Given T_0, x_0, and σ_0 constant, B can be traded off against T_b according to (16a) and (16b). However, to decrease T_b below T_0, B/B_0 must increase as the square of T_0/T_b. Thus, from a spectrum-efficiency perspective, it does not pay to increase B above B_0. An increase in bandwidth to improve accuracy seems equally unjustified. Doubling the bandwidth of Teletrac's system would presumably decrease the rms TOA estimation error at threshold from about 35 nanoseconds to about 18 ns (i.e., an improvement in rms ranging error from 35 feet to 18 feet) in the absence of multipath, which seems to be past the point of diminishing returns. For the real-world environment in which Teletrac's system typically must operate, this improvement would be completely overshadowed by the uncertainties introduced by multipath. Without multipath, 35-foot accuracy would seem to be better than adequate. Hence, in either case, there seems to be no good reason to increase the bandwidth.

In light of these relationships, the "bandwidth squared" capacity increase claimed by Teletrac (see, for example, pp. 31-32 of Teletrac's Comments and p. 25 of Teletrac's Reply Comments) is illusory. If base stations are located to take maximum advantage of their operating range (that is, $E_b/N_0 = x_0$ at the perimeter of a base station's planned coverage for the design value of N_0), then capacity can only be increased as the square root of the bandwidth if σ_t at the end-of-range is to be maintained constant. On the other hand, if there is "margin" designed